EXPLORE MOON to MARS

NASA's Challenges and Opportunities in Spaceflight Certification of Fracture Critical AM Components

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National Aeronautics and Space Administration (NASA)

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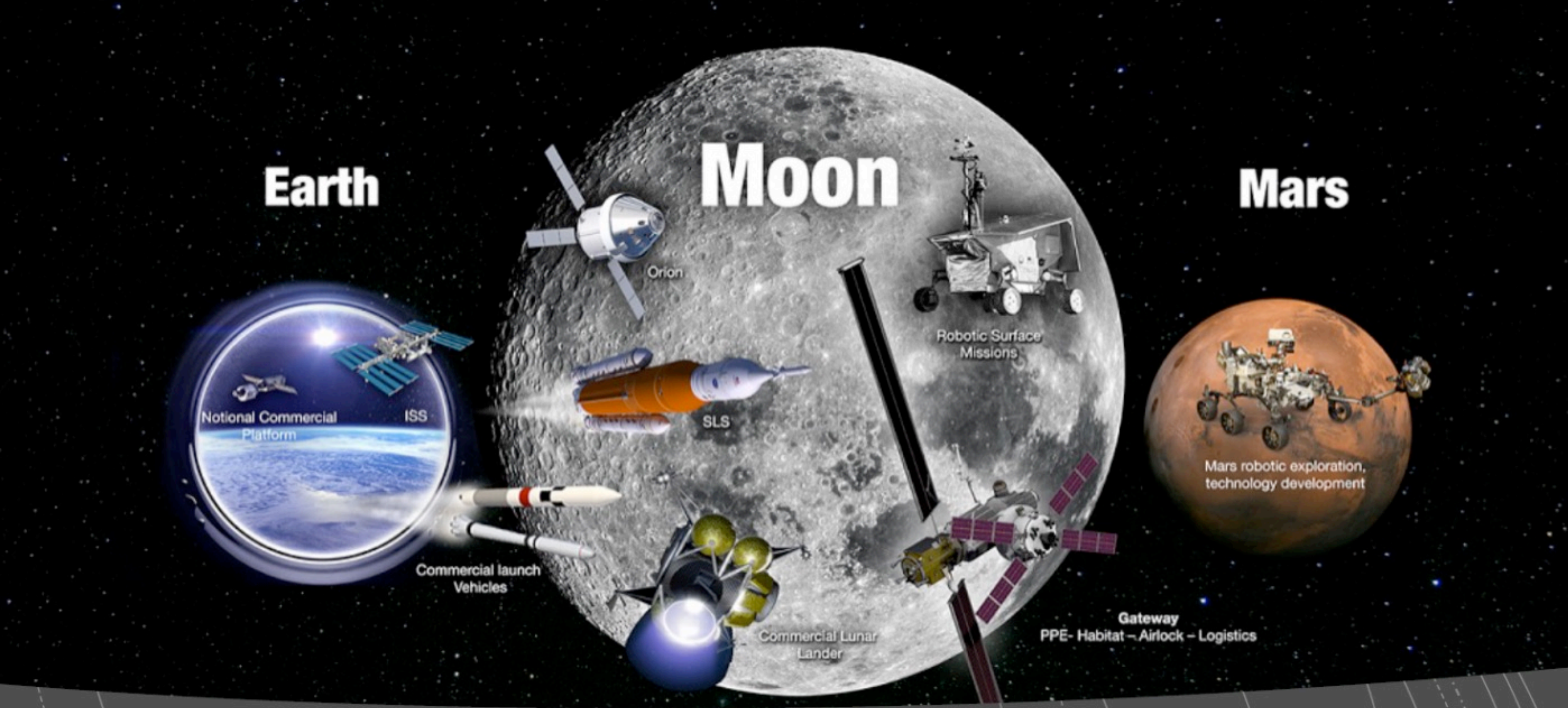


Exciting time at NASA with a lot of activities around Earth Orbit, getting ready to go to the Moon with eyes on Mars

What is NASA’s role in AM?

World of Baseball Analogy

- **Players** – Engage in technology development and infusion; drive innovation; internal NASA AM users; Commercial Partner AM users
- **Rule Book Maker; Referees; Manager, Coaches** – NASA AM Subject Matter Experts and Engineers
- **Record Keepers and Sports Commentators** – Provide public documentation of AM lessons learned and unbiased data/information
- **Fans and Baseball Commissioner -** supporting technology advancements, AM Community; Space and Science Community
- **Front Office** – funding authority, technical authority, engineering directorate, programs/projects

Overview of Presentation


Photo Credit – Paul Gradl (NASA)

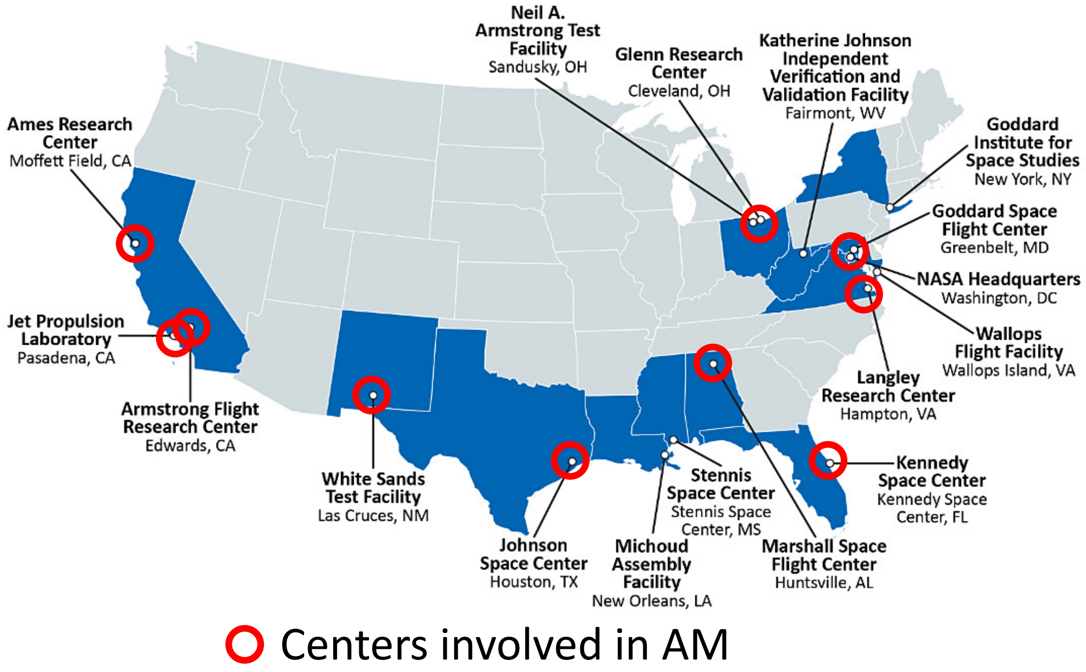
- Prolific insertion of AM hardware into NASA programs of interest
- NASA Qualification and Certification (Q&C) Strategy – basis, methodology and implementation approach
- Importance of Structural Integrity of AM components for Flight Certification
- Q&C Challenges and Opportunities

Additive Manufacturing at NASA

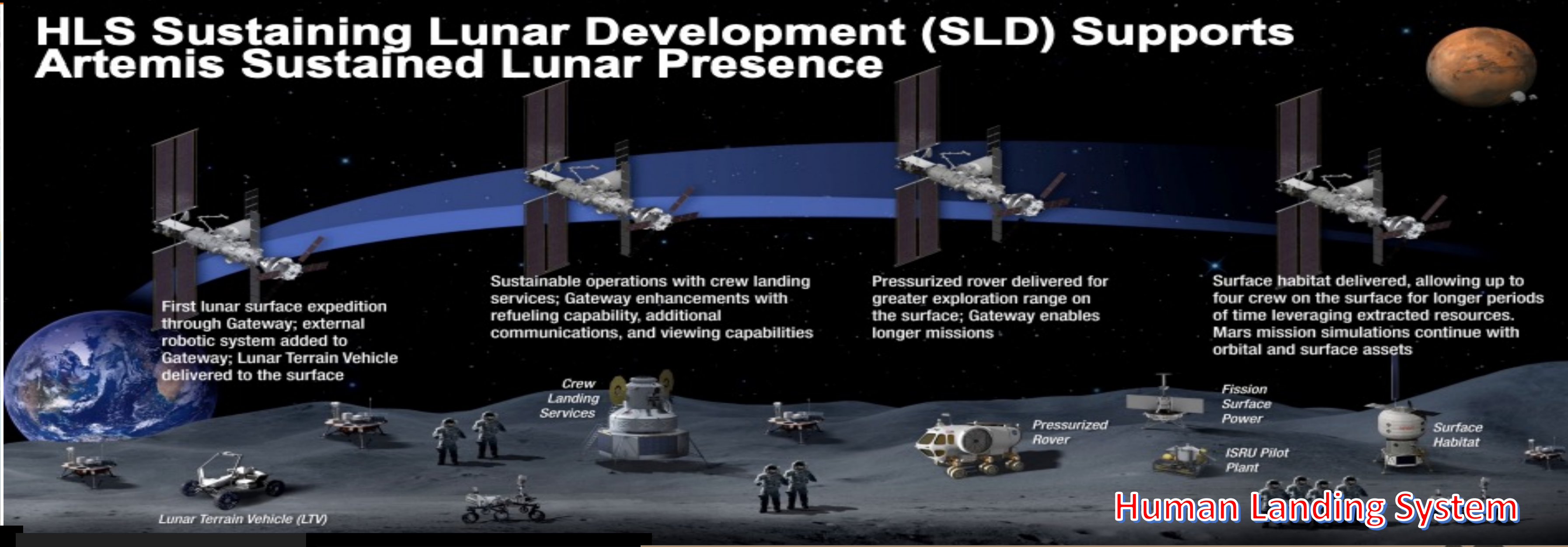
- Fully embraces advantages of AM
  - Cost/lead time/part count reduction, new design and performance opportunities, rapid design-fail-fix cycles
- While fully understanding the challenges
  - Especially in delivering high value, high performance AM hardware

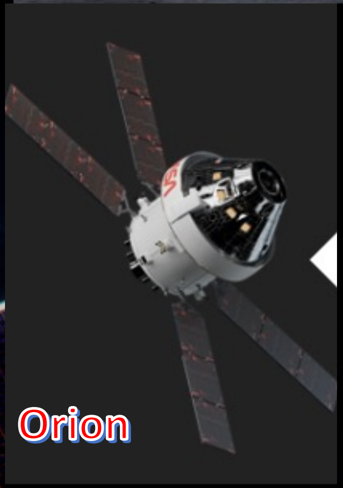
- *"NASA is an user of AM"* means…
  - NASA engineers utilizing AM processes to make hardware = NASA has the design authority
  - NASA procuring sub-system (rocket engine) or system (lunar lander spacecraft) from a commercial vendor/partner = NASA does not have the design authority; vendor does

- End goal → **Safe and successful missions**



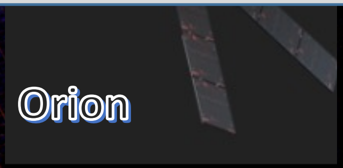
AM Insertion into NASA Spaceflight Systems

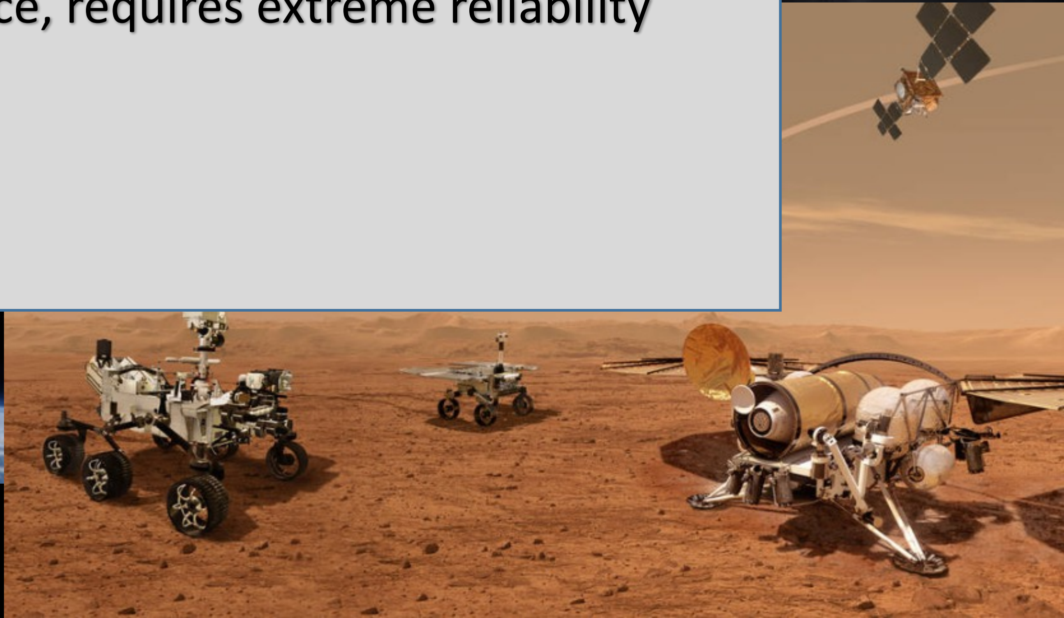




AM Insertion into NASA Spaceflight Systems

NASA moving from Low Earth Paradigm to Deep Space Paradigm
AM Parts being used in critical Spaceflight systems
Human exploration of space, especially deep space, requires extreme reliability





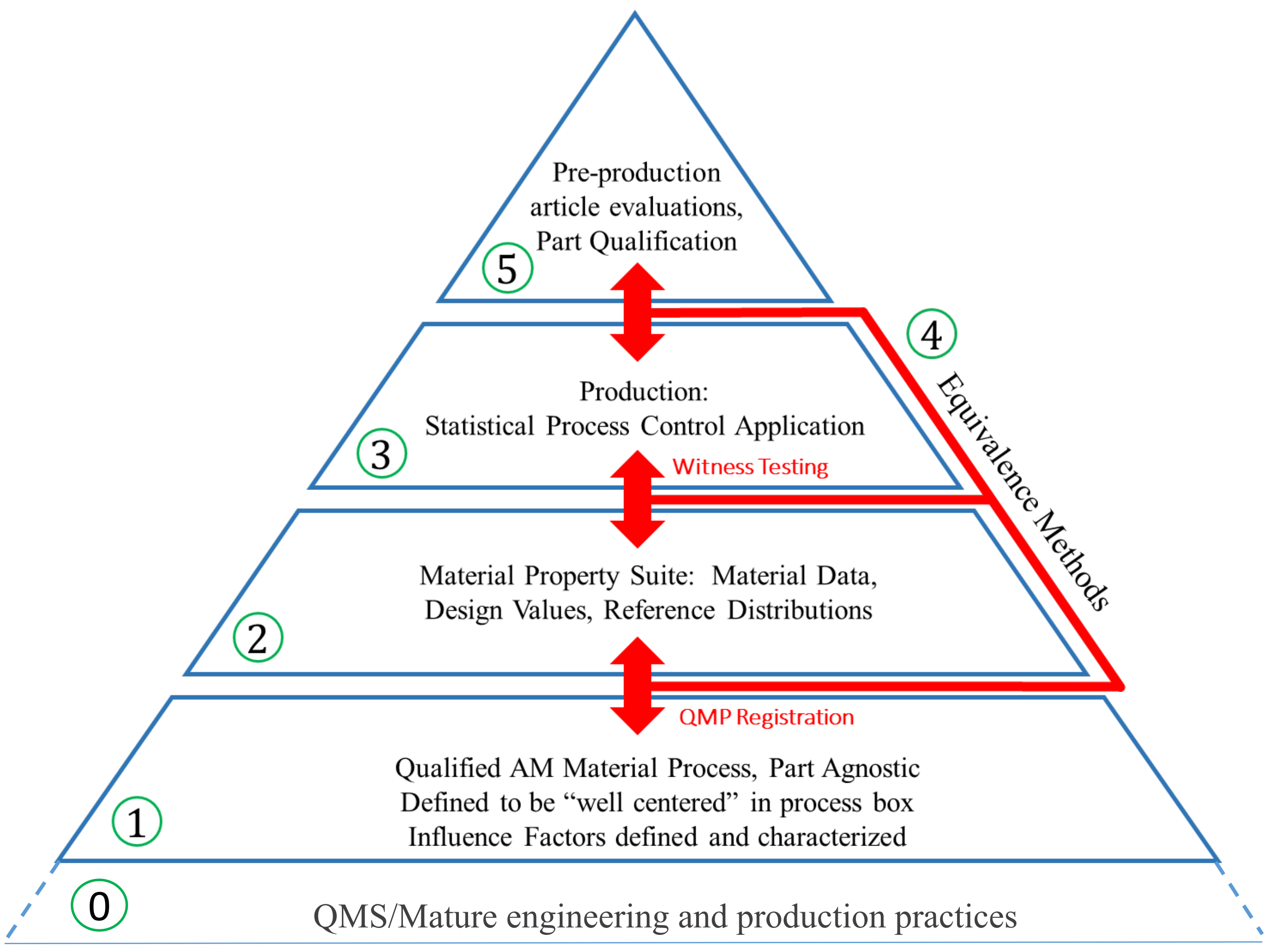
Qualification and Certification – NASA Definition

- Answer varies by industry and even by culture within industries
- The following interpretations are common within NASA:
  - **Qualification** applies to
    - Parts and components
    - Processes
  - **Certification** applies to
    - Design (e.g., status following Design Certification Review)
    - Subsystems (e.g., engine level certification test series)
    - Integrated system (e.g., collective certification for flight for launch vehicle)

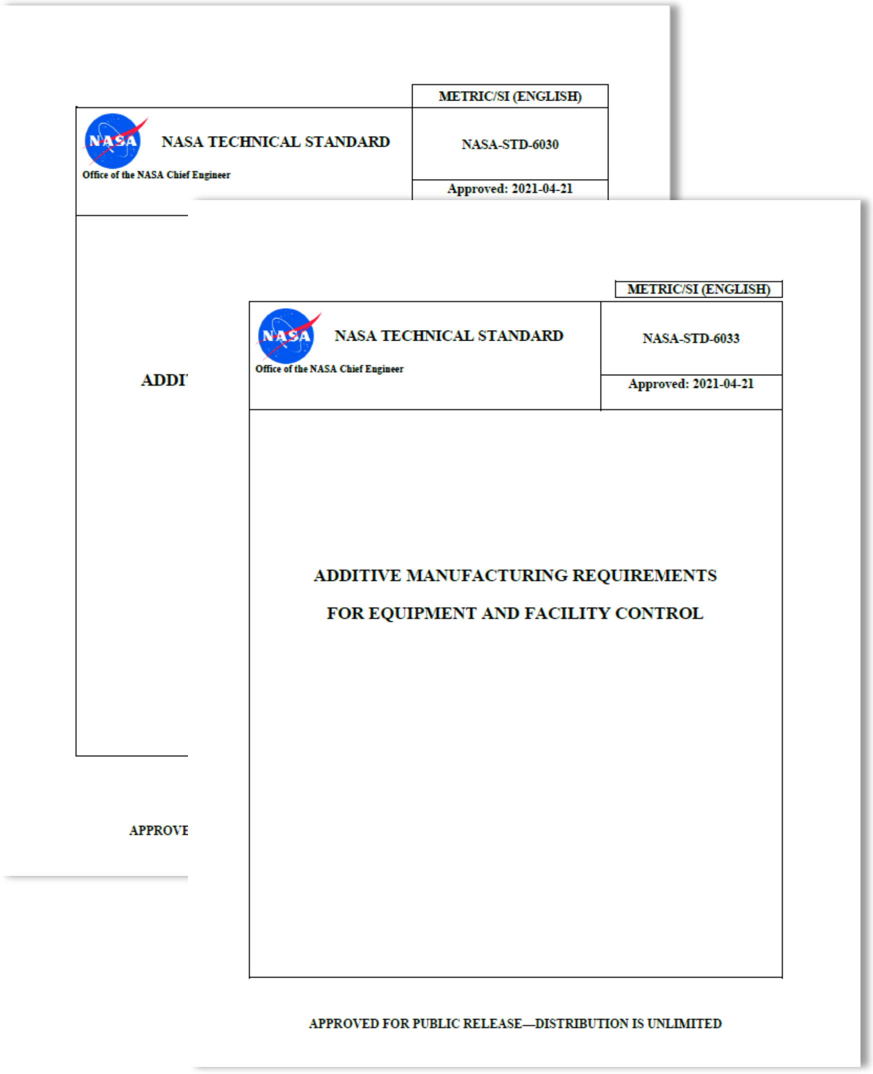
- **Good Analogy** (*credit to K. Slattery*)
  - Qualification = Final Exams, varies by subjects, teacher set the requirements, students get graded for their performance
  - Certification = Earning your diploma, need to meet minimum number of credits
  - Bottom line = developing and characterizing a stable, robust, and repeatable process is the equivalent of all the coursework and homework

NASA Q&C of AM Hardware – Backbone Philosophy

- **"Are you mature for production"**
  - Quality Management System (QMS)
  - Prerequisite – matured engineering and production practices
- **"Do you know how to define your process and how to control"**
  - Equipment/Feedstock/Fusion/Thermal process
  - Material data/Design Values/Statistical Process Control
- **"Do you understand Part Production Control Requirements"**
  - Part design, assessment and analysis, preproduction articles, and AM production controls
- **Finally, "Do you know how to establish the equivalency holistically between blocks using interrelated and causal material characteristics"**



NASA AM Standards (6030 and 6033)


METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

Office of the NASA Chief Engineer

NASA-STD-6030

Approved: 2021-04-21

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APPROVE

METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

Office of the NASA Chief Engineer

NASA-STD-6033

Approved: 2021-04-21

ADDITIVE MANUFACTURING REQUIREMENTS

FOR EQUIPMENT AND FACILITY CONTROL

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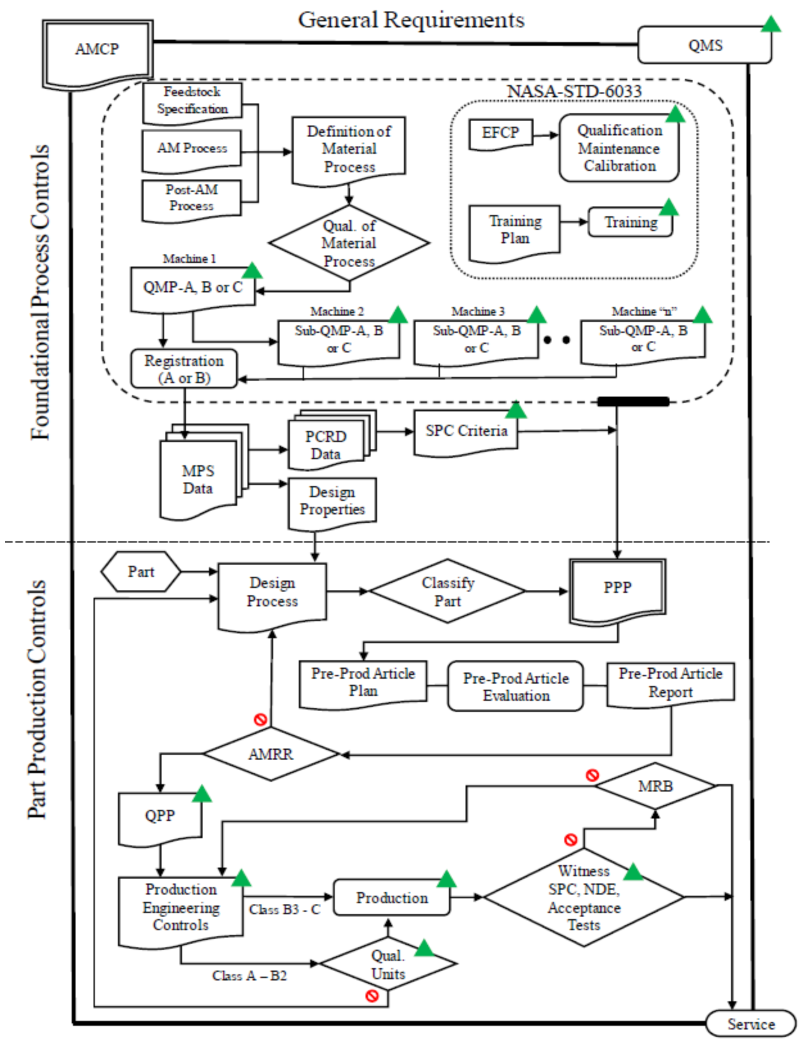
Category	Technology	Materials Form
Metals	Laser Powder Bed Fusion (L-PBF)	Metal Powder
	Directed Energy Deposition (DED), Any Energy Source	Metal Wire
	DED, Any Energy Source	Metal Blown Powder
Polymers	L-PBF	Thermoplastic Powder
	Vat Photopolymerization	Photopolymeric Thermoset Resin
	Material Extrusion	Thermoplastic Filament

https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/2021-04-21_nasa-std-6030-approveddocx.pdf

https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/2021-04-21_nasa-std-6033_-_approveddocx.pdf



Importance of Structural Integrity

- This is a notional Rocket Propulsion Turbopump Assembly – multiple AM components
- Let's say it will be a part of human-rated Launch Vehicle NASA will procure
- These components will be classified as per NASA Fracture Control Tech Standard (NASA-STD-5019) – Exempt, Non-Fracture Critical, or **Fracture Critical;** And it would be subjected to the requirements of NASA AM Standards (NASA-STD-6030 and 6033)

- **Fracture Critical –** a failure due to the presence of a crack is a catastrophic hazard
  - *Material and manufacturing processes produce structures with cracks or flaws*
  - *The presence of cracks of sufficient size reduces the strength and life of the structure*
- **Damage Tolerance –** demonstration that a component can survive the service life (with a safety factor) in the presence of an undetected flaw or damage
  - *Components are manufactured from aerospace quality materials using controlled processes*
  - *Components are inspected for damage (cracks, flaws, defects, etc.)*
  - *Components are shown by test or analysis to be tolerant to undetected flaws*

AM Fracture Critical Components – why so special?

	AM Materials	Wrought Materials
Material Quality	Material quality is highly process-dependent; variation from machine to machine.	More consistent quality due to small number of dedicated production mills with extensive experience.
Flaws	Flaws are inherent to the process Need to also worry about process-escape flaws	Flaws are typically rare
Inspectability	Inspectability varies based on component geometry; inspection techniques still under development	Raw stock is commonly fully inspectable, parts generally have high inspectability
Heritage	Little to no experience for critical applications, rapid technological development	Decades of experience

Challenge with Highly Complex AM Components

- NDE Inspections are foundational in that the inspection bounds the flaw size that might go undetected; we're "damage tolerant" - still fulfill the mission requirements if we establish the initial flaw size = largest flaw that an NDE might miss

- Real Problem : types of hardware that users desire to produce places the most complicated of geometries into critical applications (blessings of AM), but this often leads to critical AM parts with little or no access for quantitative, post-build surface and volumetric NDE (curse of AM)

- In the absence of reliable inspection to bound the initial flaw sizes, traditional Fracture control rationale does not work

- What is the Fracture Control rationale for un-inspectable Fracture Critical AM components; how do we communicate/manage the associated risks

- Alternate approach based on risk-based acceptance; thinking in the context of "distribution" (flaw size and rate of flaw occurrence); identification and control of process escapes, zone-based assessment; Probabilistic Damage Tolerance Analysis

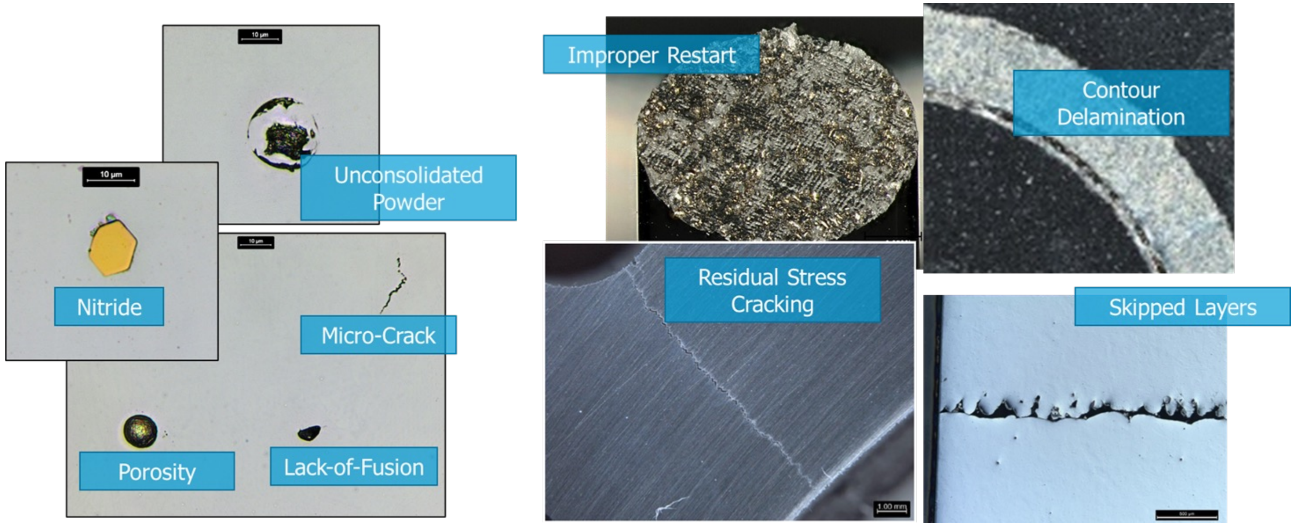
But Wait! Words Matter

- Flaw - an imperfection or discontinuity that may be detectable by nondestructive testing and is not necessarily rejectable

- Defects - one or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable

- Engineering Cracks – a flaw with sharp, flat interface that is large enough to be treated using continuum linear-elastic fracture mechanics

Flaw State Characterization



- **Inherent Flaws** - Flaws that are representative of the characterized nominal operation of a qualified AM process
  - Expected to be common enough that direct characterization is feasible. “Characterized” implies that most inherent flaws have been observed as part of AM process development and are included in the metallurgical and mechanical qualification data set
  - Not defined by size (e.g., small ≠ inherent), but are expected to be small in a well-controlled AM process
- **Process-escape Flaws** - Flaws that are not representative of the characterized nominal operation of a qualified AM process
  - Associated with some sort of process failure
  - May or may not be larger than inherent flaws, thought generally are expected to be larger
  - Have lower occurrence rates than inherent flaws
  - May or may not be detectable

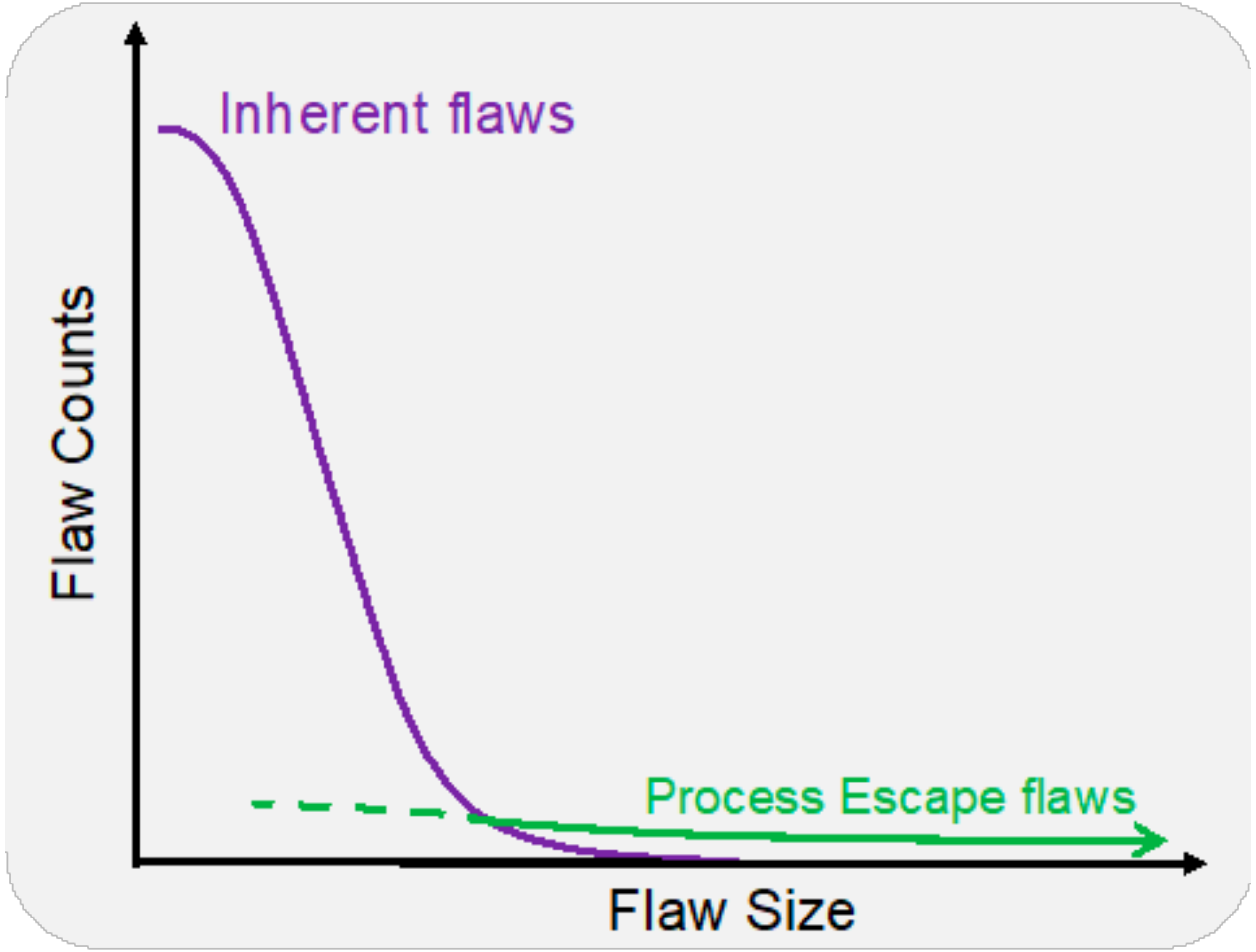
Flaw State Characterization

- Fact #1 – current metallic AM processes do not produce perfectly dense material; generate some degree of porosity, flaws, void even operating nominally

- Fact #2 – Process escape flaws are rare

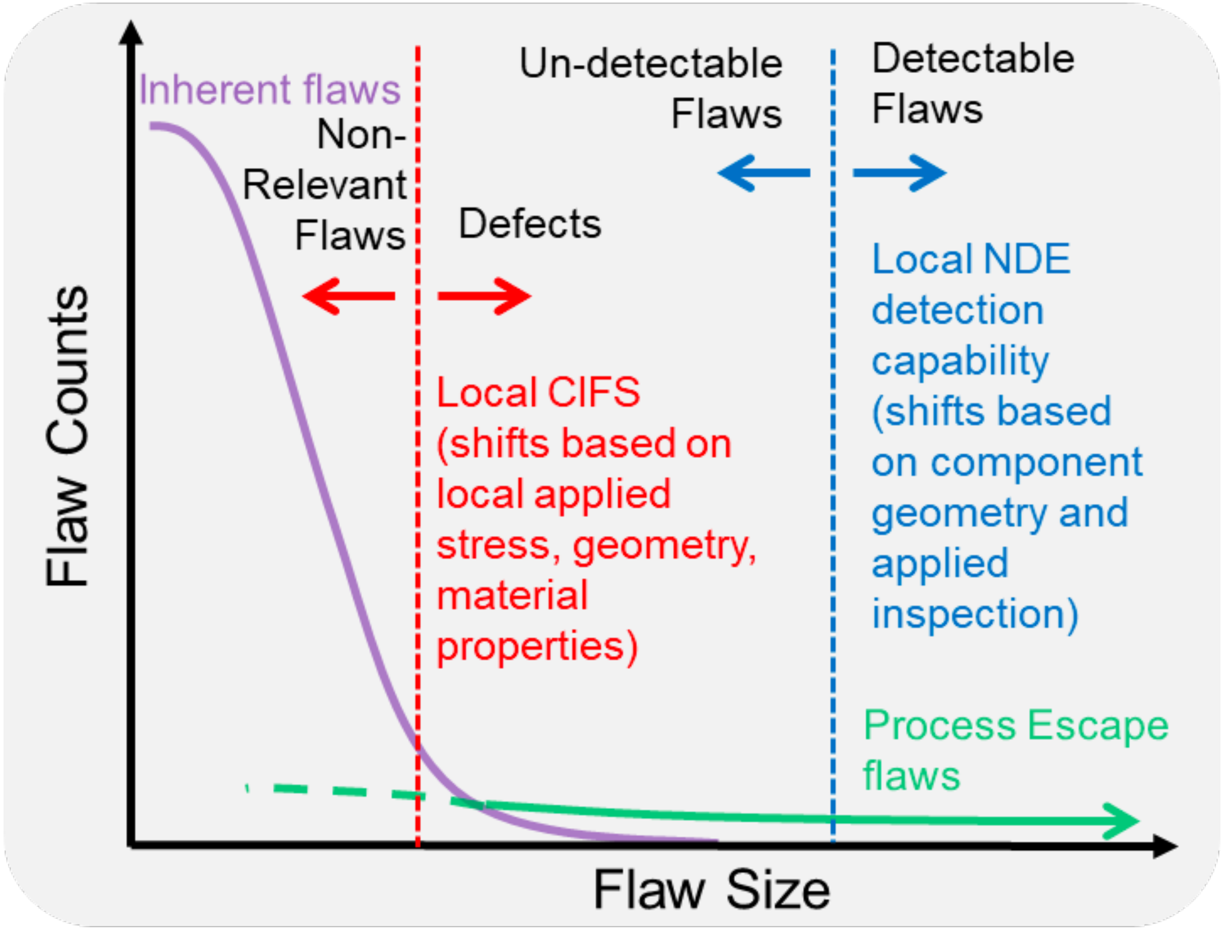
- *Systematically defining, characterizing, and controlling for [inherent] flaws that represent AM process can be used as the foundation for developing fracture control rationale for un-inspectable parts*

- *To handle process escape flaws, one should require understanding of the potential failure modes associated with AM processes (P-FMEA analysis)*



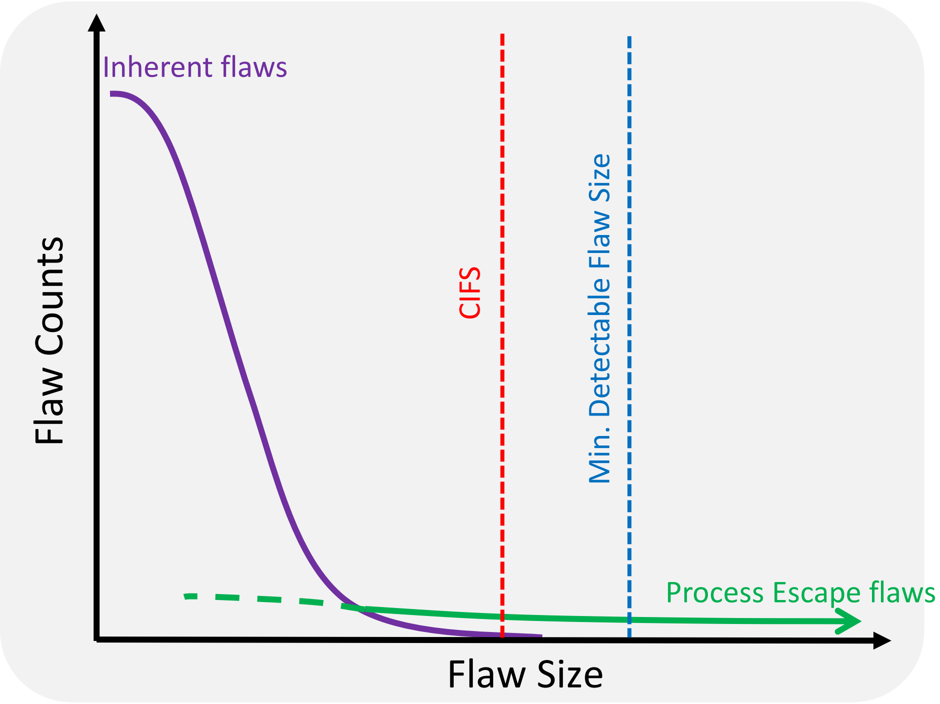
Component Assessment

- Once the flaw state distributions are defined, component specific assessment can begin
- Critical Initial Flaw Size (CIFS) – smallest initial flaw that will cause component failure within the mission life with an appropriate factor of safety
- Flaw detection capabilities
- Minimum Detectable Flaw Size – smallest flaw size that can be detected with NDE with a significant degree of reliability (e.g., 90% of time with 95% confidence)



Risk Scenario

- Scenario (un-inspectable AM hardware)
  - CIFS is larger than inherent flaw distribution
  - CIFS is smaller than NDE capability
- Possibly Approach
  - Inherent flaws are non-relevant; must focus on process-escape flaws instead
  - Think about mitigations to limit the risk of process-escape flaws
    - Rigorous PFMEA to identify potential process failures
  - Assess the risk of each process failure
    - Classic Process Controls, in-situ monitoring, machine health monitoring
    - Goal is to control process failures, not process-escape flaws
  - Probabilistic Damage Tolerance Calculations
    - Probability of fracture rather than a defined service life
    - Acceptable probability of failure → risk based acceptance
    - Unacceptable probability of failure → redesign or diff mfg process



Probabilistic Risk vs. Deterministic Life

- NASA's current practice of calculating structural integrity is deterministic yielding a (fatigue) life calculating number of cycles to failure
- Could Probabilistic Damage Tolerance Analysis provide a means of assessing the part risks in the absence of a bounding initial flaw size?
- Advantages
  - Automated tools allow for component-scale assessment of risk more robust
  - Can potentially reduce conservatism relative to the "worst-on-worst" deterministic approaches
  - Does not require extensive fatigue testing
  - Is consistent with conventional NASA's deterministic damage tolerance approach (still need to know the critical initial flaw sizes)
- Disadvantages
  - Requires extensive characterization of flaw state distributions
  - Change of paradigm : Risk vs Life
- NASA working with Southwest Research Institute on DARWIN analysis tool to develop the framework

Opportunities

- Opportunities
  - Since this approach relies heavily on accounting for and understanding all potential flaw states in AM parts, it drives the users to pay more attention on flaw characterization during the process development
  - Could accelerate the innovations in in-situ monitoring tools, advanced data analytics, ICME
  - P-FEMA practices becomes more prevalent for AM
    - Provides a means to thoroughly assess the AM process and identify the potential process escapes that would make lead to flaws. Users then can develop the rationale to mitigate that escape as identified from each failure mode

This presentation is based on (to-be-published) Proceedings of 17th ECSSMET (European Conference on Spacecraft Structures Materials and Environmental Testing), Toulouse France, March 28-30, 2023

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